DESIGN OF PULSE JET COOLANT DELIVERY SYSTEM FOR MINIMAL QUANTITY LUBRICANT (IP MQL) OPERATION

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ABSTRACT

Minimum quantity lubrication (MQL) machining is one of the promising solutions to the requirement for reducing cutting fluid consumption. The work here describes MQL machining in a range of lubricant consumption of 2.0-2.355ml/s, which is between 10–100 times lesser than the consumption usually adopted in industries. MQL machining in this range is called pulse jet coolant delivery system. A specially designed system, the IP MQL, was used for concentrating small amounts of lubricant onto the cutting interface. The performance of concentrated spraying of lubricant in pulse jet coolant delivery system design was simulated and compared with that of current 'Pulse Jet MQL' systems. The concentrated spraying of lubricant with a specially designed system was found to be effective in increasing tool life in the pulse jet coolant delivery system range.

ABSTRAK

Proses pemesinan yang menggunakan pelinciran yang berkuantiti minimum (MQL) adalah salah satu cara penyelesaian yang boleh digunakan untuk mengurangkan kuantiti penggunaan cecair pelincir. Dalam kajian ini, penggunaan pelincir MQL adalah sebanyak 2.0-2.355ml/s, di mana 10 hingga 100 kali lebih kecil berbanding penggunaan biasa di dalam proses pemesinan. MQL yang digunakan pada kadar ini dikenali sebagai sistem panghantaran penyejukan 'pulse jet'. Berikutan itu, sebuah sistem yang direkabentuk khusus untuk menumpukan semburan pelincir ke kawasan pemotongan telah digunakan. Prestasi rekabentuk sistem penghantaran penyejukan 'pulse jet MQL' yang baru disimulasikan dan dibandingkan dengan yang sedia ada. Dengan rekabentuk yang baru ini, sistem didapati cukup berkesan dalam meningkatkan jangka hayat pemotong.

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LIST OF SYMBOLS AND ABBREVIATIONS

IPMQL	-	Model of Pulse Jet Form Delivery System for Minimal Quantity Lubricant
CNC	-	Computer Numerical Control
HSM	-	High Speed Machining
rpm	-	revolutions per minutes
EDM	-	Electrical Discharge Machining
MQL	-	Minimal Quantity Lubrication
ml/min	-	milliliter per minutes
3D	-	3 Dimension
CFD	-	Computational Fluid Dynamics
BUE	-	Built-Up Edge
MPa	-	Megapascal
µm	-	micrometer
EP	-	Extreme Pressure
mm	-	millimeter
m/min	-	meter per minutes
mm/rev	-	millimeter per revolutions
mm^2	-	millimeter square
cm^3/h	-	cubic centimeter per hour
AISI	-	American Iron and Steel Institute
TiN	-	Titanium nitride
CBN	-	Cubic Boron Nitride
HP	-	Hypersensitivity Pneumonitis
OSHA	-	Occupational Safety and Health
PEL	-	Permissible Exposure Limit
NIOSH	-	National Institute for Occupational Safety and Health
REL	-	Recommended Exposure Limit
TWA	-	Time Weighted Average
STEL	-	Short-Term Exposure Limit
ACGIH	-	American Conference of Governmental Industrial Hygienists

TLV	-	Threshold Limit Value
mg/m^3	-	milligram per cubic meter
kW	-	kilowatt
AMMP	-	Centre of Advance Manufacturing and Material Processing
ø, D,d	-	Diameter
Δ	-	Distance
P	-	Pressure
E	-	Energy
u	-	Potential energy
v	-	Specific gravity
V	-	Velocity
t	-	Time
g	-	Gravity = 9.8m/s
Q	-	Flow rate
A	-	Area
π	-	Pai = 3.142
ρ	-	Density
N	-	Newton
Kg	-	Kilogram
T	-	Torque
r	-	Radius
F	-	Force
L	-	Length
Fe	-	Ferrous
C	-	Carbon
Mn	-	Magnesium
Cr	-	Chromium
W	-	Tungsten
V	-	Vanadium

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CHAPTER 1

INTRODUCTION

1.1 Background

A cutting fluid can be defined as any substance which is applied to a tool and work in metal cutting to reduce heat generated by friction, lubricate, prevent rust, and flush away chips. Cutting fluids have been used extensively in metal cutting operations for the last 200 years. In the beginning, cutting fluids consisted of simple oils applied with brushes to lubricate and cool the machine tool. Today's cutting fluids are special blends of chemical additives, lubricants and water formulated to meet the performance demands of the metalworking industry (Md. Abdul Hasib et al., 2010).

It is generally agreed that the purpose of applying cutting fluid to the metal cutting process are to reduce the rate of tool wear and to improve surface quality. The cutting fluid acts as a lubricant as well as a coolant during the operation. It reduces the surface friction and temperature on the tool-workpiece and tool-chip interfaces. The cutting fluid applied during a machining operation, can have a significant effect on the cutting temperature and tool wear. Cutting fluid also flush away chips out from the cutting area consequently protect scratch on the surface finished.

Although many advantages in the metal cutting process can be gained from the use of cutting fluid but using a large amounts of cutting fluid could pose serious problems in terms of health and environmental hazards. Operators who are exposed to the cutting fluids may have skin contact with the cutting fluids, inhale mist or vapor, or even swallow the cutting fluids. Because of their toxicity, there may be health problems such as dermatitis, problems in the respiratory and digestive systems, and even cancer. Improper disposal of these cutting fluids may cause serious environmental problems such as water, air and soil pollution.

Typically, the cutting fluid is applied under normal pressure and velocity which is known as conventional application or flood application. This application method requires a large volume of cutting fluid to apply during an operation. This large amount of cutting fluid increase the total production cost through procurement, storage, maintenance and disposal of the cutting fluid. A survey carried out in German automotive industry shows that workpiece-related manufacturing costs incurred in connection with the use of cutting fluid is at the level of 7-17% of total production cost. This is several times higher than tool costs, which accounted for approximately 2 - 4% of total production cost (Klocke and Eisenblatter, 1997). The diagram is shown in Figure 1.1.

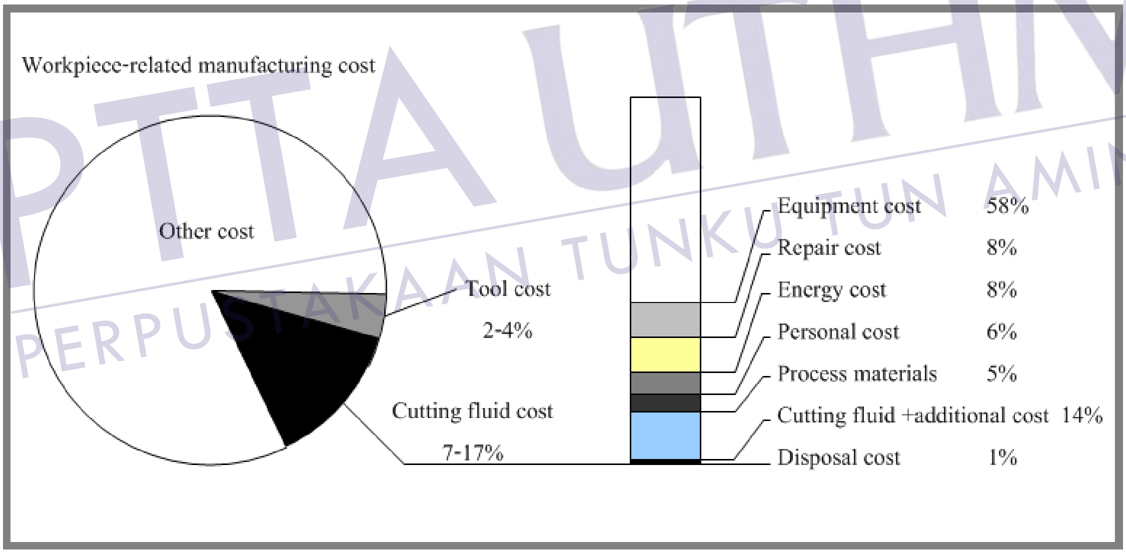

Figure 1.1: Lubricant cost exemplified by central facility (Klocke and Eisenblatter, 1997)

Dry cutting seem to be the best solution to overcome the problems posed by the use of cutting fluid. However, it is not easy to switch to dry cutting because the condition which has to be met prior switching to machining in dry mode is that dry cutting should achieve at least the same cutting time, tool life and part quality as in conventional machining with flood application (Klocke and Eisenblatter, 1997).

When a 100% dry cutting can not be realized for technological reasons, cutting with decreased use of cutting fluid is envisaged as an intermediate step (J.F. Kellya and M.G. Cotterell, 2002). The alternative lubrication strategies for a cutting process are detailed in Figure 1.2.

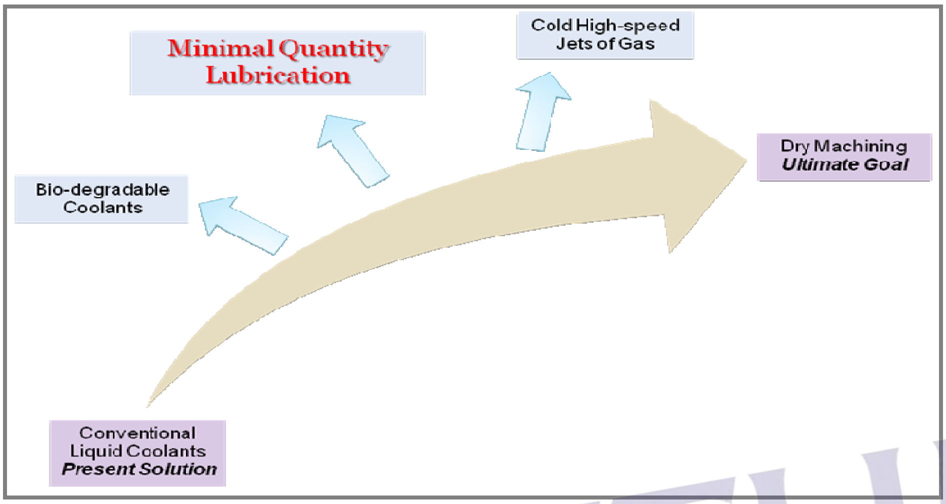

Figure 1.2: The alternative lubrication strategies for a cutting process (J.F. Kellya and M.G. Cotterell, 2002)

The phenomena mention above has led to a new trend toward the reduction of the amount of cutting fluid used or even dry machining. Nevertheless, switching from conventional flooding to dry machining requires considerations of matching the machining performance of flooding method, in term of cutting time, tool life and part quality.

A new technique called minimal cutting fluid has been introduced by A.S. Vadarajan in 2002. This method utilizes small quantities of cutting fluid in the form of high velocity and narrow pulsed jet targeted at the cutting zone. The cutting fluid consumption rate was only 2 ml/min and it showed machining performance which was superior to dry machining and flooding method in hard turning of hardened tool steel on the basis of force, tool life, surface finish, cutting ratio, cutting temperature and tool chip contact length. Anyway, the cutting condition in continuous cutting process of turning is different from intermittent cutting process of milling which involves rotating cutter with multiple cutting edges. Effectiveness of minimal cutting fluid in milling process may be different from turning process and problems such as thermal shock in intermittent cutting process, caused by cutting fluid may occur (A.S. Vadarajan, 2000).

In 2005 an investigation of the minimal cutting fluid technique in high speed milling of hardened steel with carbide mills was done by Thanongsak Thepsonthi. Cutting fluid was applied in the form of high velocity and narrow pulsed jet at the rate of 2 ml/min and the machining performance was compared to flood and dry cutting. The findings of the study show that machining with minimal cutting fluid application can be adopted as a replacement of flood and dry cutting. The research was done using three different cutting modes, which are MQL, flood and dry cutting commonly used in machining operations. Each of these cutting modes has been used with ceramic cutting tool. Study on the machining performance comparison for these cutting fluids has not been investigated and the cutting fluid which has the better machining performance has not been determined (T.Thepsonthi et al., 2009).

Thus, the minimal cutting fluids application in pulse jet form has shown to be a viable alternative to the current, flood and dry cutting method that are used widely in industries. However, to comply with industry application, the system needs an improvement because recent research only introduced the basic technique – Lab prototype. Therefore, this study would explore the feasibility of designing MQL application technique which can be used in more advanced machining strategies. Evaluations would be made on the newly designed system and compared to existing technique.

1.2 Objectives

There were three main objectives in this study;

(i) To design a new technique of pulse jet form delivery system for minimal quantity lubricant (IP MQL).

(ii) To calculate the important parameters of IP MQL and compare with simulation.

(iii) To compare the performance of IP MQL with MQL application prototype, conventional flood application and dry application in slot milling machining process.

1.3 Scope of the study

This study is concentrated to the design and development of IP MQL operations. The system is used in order to concentrate small amounts of lubricant onto the cutting interface. The performance of concentrated spraying of lubricants in IP MQL system was simulated and compared to MQL application prototype, conventional flood application and dry application by using experimental method. Experiments were conducted using high speed milling machine and specifically on slot milling cutting. The experiment measures cutting forces, tool wear and surface roughness.

1.4 Research Methodology

There are six stages in the research methodology which include (i) literature reviews, (ii) setting up the research strategies, (iii) data collection and evaluation, (iv) design process, (v) data analysis and lastly, (vi) documentation of findings. The details of task in every stages are illustrates in the points below. The flow of the process is also explained in chart as shown in Figure 1.3.

Stage I: Literature Review

This introductory stage gathers information on history and theories of general information on cutting fluid and its functions in machining process, and the present method of cutting fluid application, from the typical flood application until the development of minimal cutting fluid application. The works associated with minimal cutting fluid application are also presented in this section. The issues related to the use of cutting fluid are explained at the end of the chapter.

Stage II: Setting up the research strategies

Information gathered in literature review gives insight on the existing MQL system, function and specification where the system requirement leads to the introduction of the new mechanism. In this stage, several design concepts were developed according to the parameters and system requirement in order to select the optimum design concept. The design calculation also involved before generating the 3D drawing. Hence, to ensure the design can optimize its performance, Computational Fluid Dynamic simulations (CFD) analysis were carried out to analyze the pressure and velocity.

Stage III: Data collection and evaluation

In this stage of research works, data from preliminary sources were collected and some evaluation carried out to locate the suitable major variables. The evaluation were measured based on calculation, simulation and experiment before proceed to the next stage.

Stage IV: Design process

The data collected from earlier stage encouraged the design process. In this stage, the planning simulation tool requirements were setting up. After selection of design concept in the previous section, the simulation of design developed and calculation were done. The process also to evaluate whether there were any improvement to the previous design process and modification will be made to the result afterwards.

Stage V: Data analysis

The focus of the analysis is to identify the machine tools, cutting fluid delivery, type of cutting tool and work piece used in the research. Then, the following part explains the experiments were conducted and the data collection. The experiments were conducted in slot milling process which is generally applied to ball end milling. The experiments were done in many different levels of cutting parameters in order to explore a cutting performance of IP MQL application and compare it to MQL application prototype, flood and dry cutting (T.Thepsonthi et al., 2009). The results of this study show the performance of the IP MQL in terms of cutting force, surface roughness, and flank wear.

Stage V: Documentation of findings

The results of significances performance of IP MQL lubrication techniques in high speed end milling of hardened steel were present clearly in Chapter 5 and 6. The results evidently indicate the advantages of using this IP MQL in pulsed jet. Cutting forces, surface roughness, and tool wear were affected beneficially when using the IP MQL mode.

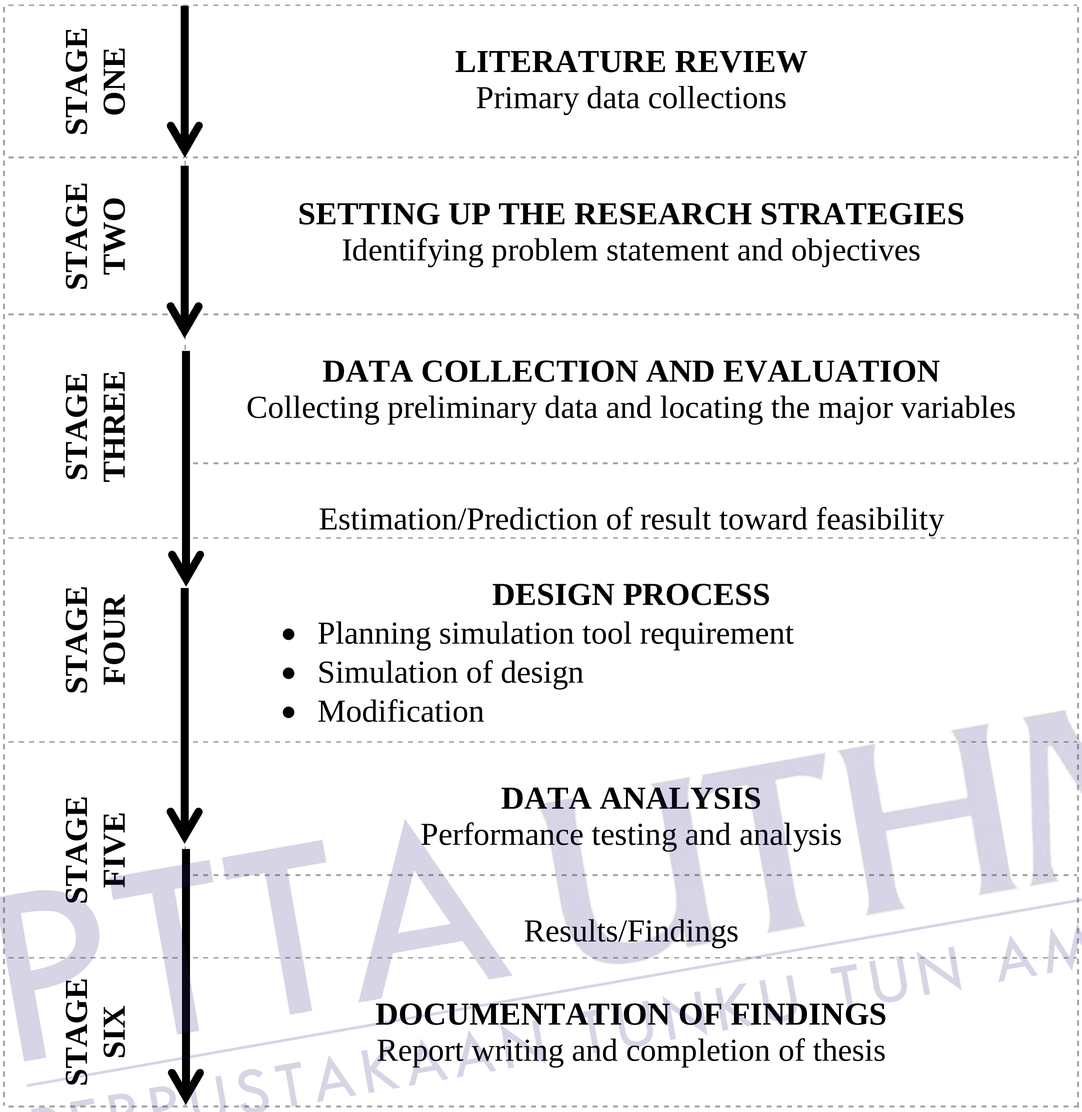

Figure 1.3: The flow of stage in the research process.

1.5 Organization of the thesis

This thesis consists of six chapters. The contents of each chapter are explained as follow.

Chapter 1 gives the background of the problems studied in this thesis, as well as the scope and objectives of the research work.

Chapter 2 give literature review contains two important parts. First is general information on cutting fluid and its use in machining process, as well as a conventional application technique. Second part is a summary of the research that has been done in to minimize cutting fluid used in machining process.

Chapter 3 describes the IP MQL system development process. From the MQL application prototype system function and specification, the new mechanisms were designed based on the system requirements. Several concept designs were developed and chosen according to the system requirement and interest. After going through the evaluation of concept designs using the basic matrix, the optimum design were selected. All the mechanical and controller parts were identified to meet the specification. Appropriate 3D drawings were generated for the part and components. The designs were go through the CFD simulation for the confirmation of parameters.

Chapter 4 describes the work pieces, tools and all equipments used in this research. An experimental setup and procedure are explained here in detail. Cutting forces, tool wear and surface roughness are plotted in graph against cutting parameters

Chapter 5 presents the discussion on the performance of IP MQL application compared to MQL application prototype, conventional flood application and dry machining.

Chapter 6 presents the conclusion of the research work and its contribution to the machining process. Several recommendations are also suggested for further development.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of the existing literature relating to the delivery cutting fluid system. It introduces the general information on cutting fluid and its functions in machining process, and the present method of cutting fluid application, from the typical flood application until the development of minimal cutting fluid application. The works associated with minimal cutting fluid application are also presented in this section. The issues related to the use of cutting fluid are explained at the end of the chapter.

2.2 Cutting fluid functions in machining process

Cutting fluids typically perform numerous functions simultaneously, including cooling and lubricating the tool-workpiece and tool-chip interfaces, minimizing the effect of built-up edge (BUE), protecting the workpiece from corrosion, and flushing away chips. However a good cutting fluid must serve two important basic functions, namely cooling and lubrication.

2.2.1 Cooling function of cutting fluid

Cutting fluids initially were thought to act primarily as coolants (M.A. El Baradie, 1996). By flowing over the tool, chip and workpiece, a cutting fluid can remove heat and thus reduce temperature in the cutting zone.

In order for a cutting fluid to function effectively as a coolant, two requirements must be met. The cutting fluid must gain an access to the source of heat, and the fluid must have the thermal capability of removing the heat.

The properties of a cutting fluid which determine its ability to cool are its thermal conductivity, specific heat, heat of vaporization, and wet ability with metal surface (M.A. El Baradie, 1996). Water fulfils this requirement and has the additional advantage of being inexpensive, but it is a poor lubricant and therefore is not effective in reducing friction between chip and tool face. In addition, it is corrosive to ferrous metals and so cannot be tolerated in high end machine tools. Moreover, it tends to wash the lubricating oil from the sliding and rotating the surfaces of the machine, thus reducing the smoothness of running and increasing wear (M.A. El Baradie, 1996).

Generally a reduction in temperature results in a decrease in wear rate and an increase in tool life. This occurs because, first, the tool material is harder and so more resistant to abrasive wear at lower temperatures, and secondly, the diffusion rate of constituents in the tool material is less at lower temperatures (M.A. El Baradie, 1996). Opposing these two effects, a reduction in the temperature of the workpiece will increase its shear flow stress, so that the cutting force and power consumption may be increased to some extent. Under certain conditions this can lead to a decrease in tool life (M.A. El Baradie, 1996).

Particularly, to clarify the condition of decreasing in tool life, the cooling effect is important in reducing thermal expansion and distortion of the work piece. The cooling action does not have a very significant effect on the surface finish produced. It can, however, bring about some small improvements in the surface finished at medium to low speeds. This is probably due to the chip formation which increase chip curl and reduce built-up edge formation (M.A. El Baradie, 1996).

2.2.2 Lubrication function of cutting fluid

Lubrication, as defined in most theories, considers two sliding surfaces, and it depends on the ability of the fluid to penetrate the interfaces of the cutting zone. If the lubricant can penetrate into the chip tool contact area, it will reduce the contact length and decrease the forces, heat generation, temperatures and tool wear. Its ability to improve surface finish is attributed to the fact that it can lubricate the rake face and avoid formation of built-up edge (BUE), by minimizing adherence. If the lubricant cannot penetrate the entire contact length it could at least lubricate part of the contact where there is no strong adherence (the sliding zone) reducing the shear stress distribution on the rake face, reducing the energy, as well as temperature.

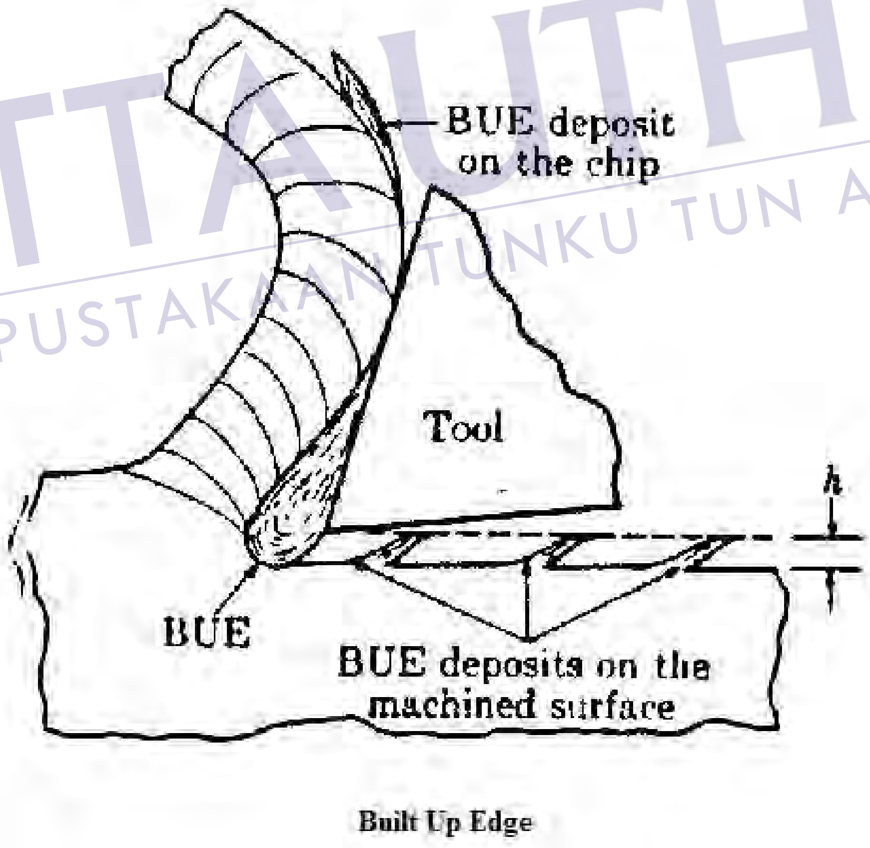

Figure 2.1: Built Up Edge (BUE) diagram (M.A. El Baradie, 1996).

Surface cleanliness is one of the most important parameters affecting the friction coefficient. Even a single molecular layer of contaminant from the atmosphere may produce a very large decrease in friction. In machining, the underside of the chip and the machined surface are newly formed surfaces and are in close contact with the tool. They rub against the tool surface, removing oxide coatings and any other contaminant. Thus, the surfaces can metallurgically bond together. This bonding and the motion of the surfaces tend to exclude cutting fluid (Wright et al., 1979).

It is not clear yet what access a cutting fluid has to these interfaces or how it can get there. The average normal stress on the chip tool contact zone is extremely high, being in the range of 200-800 MPa for steel (Trent, 1988). At high cutting speed where the temperature is high, further problems are encountered as the lubricant may get boiled or decomposed before penetrating the cutting zone. On the rake face during cutting (at high speed), there are seizure zones and sliding zones. The length of these depends on the stress distribution on the tool. There is some support (Childs and Rowe, 1973) for the theory that a lubricant cannot gain access to the seizure zone and so attention should be focused on the sliding region. If the lubricant is applied and it penetrates only the sliding zone, which makes only a small contribution to the total forces, it will only marginally affect the total force. The sliding zone has the lowest compressive forces and as such can be influenced by small changes in the cutting process. Lubricants may be able to decrease the effective stick slip situation in this zone and give a smoother cutting action. This same phenomenon could happen at the flank face.

As the cutting speed increases the temperature increases, which means that coolant properties become more important, and lubrication becomes much more difficult. Neat cutting oils used at high speeds often exhibit signs of decomposition in the form of smoking, which renders them unsuitable (Marcio Bacci da Silva et al., 1998). The term of neat cutting oil refers to those based predominantly on mineral oil (M.A. El Baradie, 1996).

2.2.3 Cutting fluid accessibility

Cutting fluid accessibility depends on cutting geometry, severity of the operation, properties of the fluid and to some extent, condition and nature of the workpiece material. It is not completely clear how a cutting fluid actually manages to penetrate to the deformation and friction zones since (1) the relative motions of the chip, tool and workpiece combine to carry fluid away from the cutting zone and (2) the contact pressures between the tool and the material can be extremely high.

Several mechanisms have been proposed to account for the ability of the cutting fluid to penetrate the system. Some researchers suggest that the present of small (on the order of 0.0001-2.5 μm) crevices or fissures at the interface allows fluid to spread by capillary action (Thomas J. Drazda and Charles Wick, 1983). Other researchers believe that some cutting fluid penetrates through the metal lactic via a diffusion mechanism. However, it is not well supported by evidence. Another proposed mechanism is the volatilization of a liquid to a gas of much lower viscosity, allowing the gas to penetrate the cutting zones (Thomas J. Drazda and Charles Wick, 1983).

The most persistent alternative mechanism is the "Rehbinder effect" observed with certain surface active additives. Although the details of the effect are not well understood, it is believed that the surface-active species (usually chlorine) interact with the workpiece material to reduce the shear strength in the primary deformation zone.

2.3 Types of cutting fluid

Although hundreds of cutting fluids and special formulations exist for cooling and lubricating metal cutting operation, there are four major classes of metal-working fluids widely available: Neat cutting oil, soluble oil, semi synthetic, and synthetic. Numerous metal working fluids, except the neat cutting oils, are mixed with water for use. Each has additives such as surfactants, biocides, extreme pressure agents, anti-oxidants, and corrosion inhibitors to improve performance and increase fluid life. Figure. 2.2 shows the classification of cutting fluid.

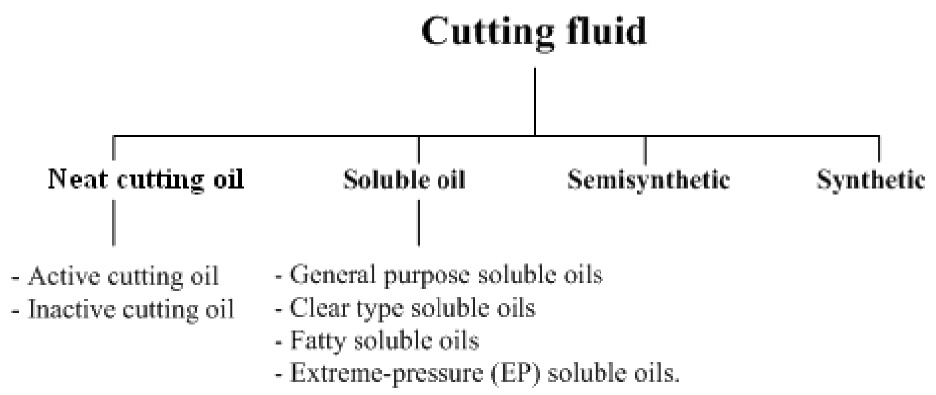

Figure 2.2: Classification of cutting fluid (M.A. El Baradie, 1996)

2.3.1 Neat Cutting oil

The term of neat cutting oil refers to those based predominantly on mineral oil and use as supplied i.e. not mixed with water. This type of metalworking fluid is made up mostly of mineral (petroleum) or vegetable oils (M.A. El Baradie, 1996).

It may be used straight (uncompounded) or compounded with polar additives or/and chemically active additives. Common polar additives include animal and vegetable oil, derivation of castor oil and synthetic sperm oils. Chemically active additive include sulfur, chorine and phosphorus.

Neat cutting oil is generally used for processes that require lubrication rather than cooling. They perform best when used at slow cutting speeds, low feed rate, and high metal-to-metal contact or with older machines made specifically for use with cutting oils.

There are two main types of compounded neat cutting oils. The first is inactive cutting oils, these neat cutting oil are mineral oils compounded with chemically inactive additives. In general they provide high lubricity and are non-staining, but exhibit limited anti weld properties. The second is active cutting oils, it contains sulfur, chlorine, and/or phosphorus in an active form blended with mineral oil or fatty mineral oil blends. These chemical additives, extreme-pressure lubricants, provide a tough, stable film of the lubrication at the tool-chip interface. They are particularly useful in extending tool life in high temperature and high pressure applications. Active neat cutting oils include sulfurized mineral oil, phosphorized mineral oil, sulfa-chlorinated mineral oil, and sulfa-chlorinated fatty oil blends. Lots of chemical active cutting oils may stain certain metals.

2.3.2 Soluble oil

Soluble oils are commonly called emulsifable oils, emulsions or emulsifiable cutting fluids. An emulsion is a suspension of oil droplets in water made by blending the oil with emulsifying agents and other materials. These emulsifiers (soap or soap like materials) break the oil into minute particles and keep the particles dispersed in water for long periods of time.

Bactericides which are usually nonphenolic organic compounds are added to control the growth of micro-organisms such as bacteria, algae and fungi. If disposal is of no concern, phenolics may be used. The soaps, wetting agents, and couplers used as emulsifiers in water soluble fluids reduce surface tension significantly. As a result, the liquid has a greater tendency to foam when subjected to shear and turbulence. For this reason, soluble fluids sometimes cause foaming problems in operations such as gun-drilling and double-disk grinding. With the use of special wetting agents and foam depressants, however, water soluble fluids can be rendered sufficiently nonfoaming to be effective in almost all operations (M.A. El Baradie, 1996).

Soluble oils combine the lubricating and rust prevention properties of oil with water's excellent cooling properties. Emulsions, with their cooling lubricating properties, are most effectively used for metal cutting operations with high cutting speeds and low cutting pressures accompanied by considerable heat generation.

Advantages of soluble oils over straight or compounded cutting oils include greater reduction of heat, cleaner working conditions, economy resulting from dilution with water, better operator acceptance and improved health and safety benefits. They can be used for practically all light and moderate duty cutting operations, as well as for most heavy duty applications except those involving extremely difficult to machine materials.

Soluble oils can be used for practically all grinding operations with the exception of severe grinding operations, such as form, thread and plunge grinding where wheel form is a critical factor. Extreme pressure, compounded soluble oils do not suffer from this limitation.

Cutting fluid manufacturers supply soluble oils as concentrates that the user prepares by mixing with water. Mixtures range from 1 part oil in 100 parts water to a 1:5 oil water ratio. The leaner emulsions are used for grinding or light duty machining operations where cooling is the essential requirement. Lubricating properties and rust prevention increase with higher concentrations of oil.

Generally, soluble oil can be divided into four main types, general purpose soluble oils, clear type (or translucent) soluble oils, fatty soluble oils and extreme-pressure (EP) soluble oils (M.A. El Baradie, 1996).

General purpose soluble oils: it is milky fluids with mineral oil droplets of 0.005mm to 0.2mm diameter. It is commonly used at dilutions of 1:10 to 1:40 for general purpose machining (M.A. El Baradie, 1996).

Clear type (or translucent) soluble oils: clear type soluble oils contain less oil (with higher proportions of corrosion inhibitors) and considerably more emulsifier than do milky emulsions. The clear type, therefore, consists of oil dispersions with smaller oil droplets which are more widely distributed. Since there is less dispersion of transmitted light, the fluid is less opaque, and the result is a translucent liquid. The translucency is not permanent, though, because often with times the tiny oil droplets tend to coalesce and from larger droplets. These oils are generally used for grinding or light duty machining.

Fatty soluble oils: it have animal or vegetable fats or oils or other esters added to the mineral oil content to provide a range of fluids with enhanced lubricating properties.

Extreme-pressure (EP) soluble oils: EP soluble oils contain sulfur, chlorine or phosphorus additives to improve load carrying performance. Since the EP concentrate is diluted 5 to 20 times when the emulsion is prepared, the lubricating capability is reduced. Where the lubricating capabilities of soluble oil emulsions and the cooling properties of cutting oils are inadequate, EP soluble oils can satisfy both requirements in many cases. These fluids, commonly known as heavy duty soluble oils, have in some cases replaced cutting oils for broaching, gear hobbling, gear shaping and gear shaving (Metcut Research Associates Inc., 1980).

Drawbacks in using soluble oils, however, it is sometimes have poor corrosion control, sometimes dirty (i.e., machine tool surfaces and nearby areas become covered with oil or difficult-to-remove product residues), may smoke (it may not cool as well as semi synthetics and synthetics), and may have poor mix stability or short sump life.

2.3.3 Semi synthetic

This type of metalworking fluid contains a lower amount of severely refined base oil, for example, 5-30 percent in the concentrate (Metcut Research Associates Inc., 1980). Semi synthetics offer good lubrication, good heat reduction, good rust control, and have longer sump life and are cleaner than soluble oils. They are comprised of many of the same ingredients as soluble oils and contain a more complex emulsifier package.

2.3.4 Synthetic

These metal working fluid formulations do not contain any petroleum oil. It contains detergent-like components to help wet the part and other additives to improve performance. Like the other classes of water-miscible fluids, synthetics are designed to be diluted with water.

Among the four types of fluids, synthetic metalworking fluids generally are the cleanest, offer the best heat reduction, have excellent rust control, and offer longer sump life. In addition, this type of metalworking fluid is transparent (allowing the operator to see the work) and are largely unaffected by hard water.

2.4 Cutting fluid application

The normal way of applying a cutting fluid is called flood application. Large volumes of cutting fluid are applied to the cutting zone as a continuous flow at low to moderate pressure. It is very efficient in chip removal. However, at higher cutting speed, it has been proved that the cutting fluid lose its effectiveness as a coolant. Because of the inability of cutting fluid to reach the region to be cooled and the tendency of the faster moving chip to carry out the cutting fluid away from the cutting zone (R. Kovacevic et al., 1995).

In 1952 the high pressure jet application method has been started (Piggot and Colwell, 1952). Pressurized cutting fluid is injected into a cutting zone through a remote nozzle or through the tool rake face. This method is much more beneficial than conventional flood application (R. Kovacevic et al., 1995; P. Dahlman, 2002).

However, the amount of cutting fluid used in flood application and high pressure jet application compared with the small areas of contact in the cutting zone that should be affected, a very small volume of fluid should be enough to lubricate the entire contact area. If a typical machining operation is considered, a cutting speed of 200 m/min, 2 mm depth of cut and a feed rate of 0.2 mm/rev then the area of the lower surface of the chip which is produced every minute is approximately 400,000 mm^2. To effectively lubricate, the surface of the cutting fluid must interject this interface to at least one molecular layer. This would require a cutting fluid about 7.2×10^{-4} cm^3/h. Assuming and efficiency of 1 % coverage the total cutting fluid required will be approximately 0.1 cm^3/h (A. R. Machado and J. Wallbank, 1997). Therefore practical machining applies much more cutting fluid than is required to just contaminate this interface. If the amount of cutting fluid used can be drastically reduced without affecting the process many of the problems caused by cutting fluids may be minimized. Some techniques to apply a small quantity of the cutting fluid have been innovated and investigated during the last decade. The most researchers paid attention in applying extremely low quantities of oil in compressed air stream or so-called mist application.

A. R. Machado and J. Wallbank (1997) conducted experiments on turning of medium carbon steel (AISI 1040) using cutting fluid amounting to 3.3–5 ml/min, which was applied in a fast flowing air stream of 0.2 MPa through a special venturi designed to mix compressed air with small quantities of a water and soluble oil. Figure 2.3 shows the schematic diagram of the venturi used by them. The result showed that surface finish, chip thickness and force variation were all affected beneficially compared to those obtained by the flood coolant at flow rate of 5,200 ml/min.

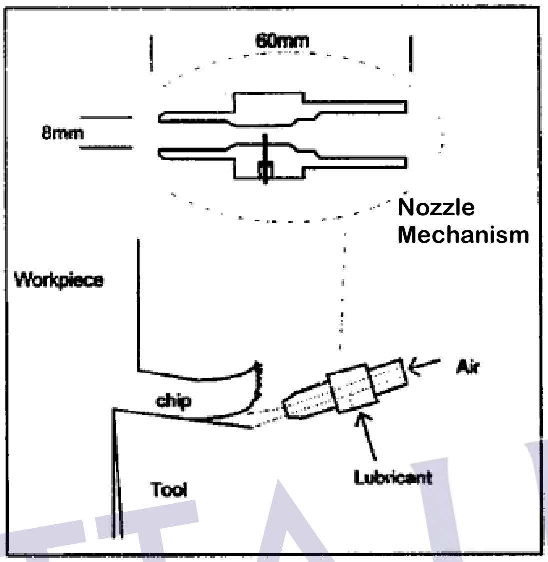

Figure 2.3: The schematic diagram of the oil air venturi (A. R. Machado and J. Wallbank, 1997)

In a study by Toshiaki Wakabayashi et al. (1998), air containing uniform and extremely low concentration (0.01–0.16 ml/min) of cutting oil was discharged on the rake face and flank face of a turning tool at a pressure of 0.6 MPa. Considering 4,000 ml/min as the conventional cutting fluid benchmark, it was concluded that the result was almost equal to conventional method in terms of prevention of tool wear, improvement of surface finish and control of built-up edge.

Tea Jo Ko et al. (1999) used the oil mist application for the turning of hardened materials. The cooling system relies on a vortex tube for cooling the ejected air, and the liquid coolant supplied at the cooling nozzle formed into a mist by the air. In this system, the air temperature at the outlet was lowered by more than 20°C. This system is similar to a conventional mist coolant system except that it uses cooled air. In the experiments, the cooled air with oil mist ejected at the tip of the cutting tool lowers the tool temperature, and reduced the wear of a TiN coated tool to give 30% of CBN tool life at the same cutting length. Figure 2.4 shows the schematic diagram of the air vortex tube.

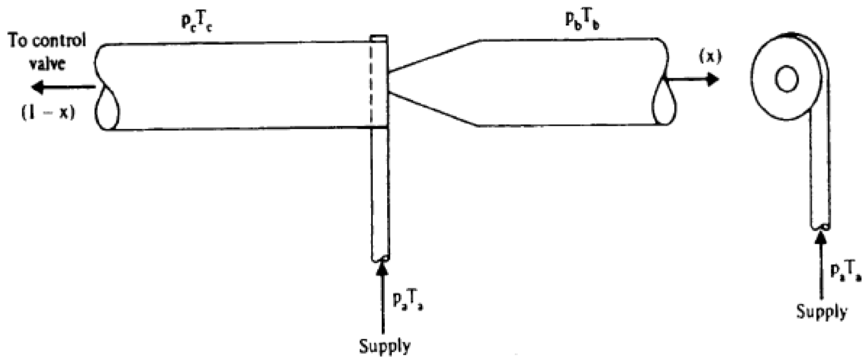

Figure 2.4: The schematic diagram of the air vortex tube (Tea Jo Ko et al., 1999)

M. Rahman et al. (2002) have done the experiment in end milling using a superfine particle oil mist generator to apply 0.15 ml/min of cutting fluid at a pressure of 0.52 MPa. Results indicated that mist application can be considered as an alternative to flood application at 42,000 ml/min owing to the drastic reduction (1/300,000 times) in lubricant consumption.

Durval U. Braga et at. (2002) have done a research on drilling of aluminum-silicon alloys using 10 ml/h of oil in flow of compressed air (4.5 bars). The result showed that minimal cutting fluid application has the similar performance compared to flood application.

T. Aoyama (2002) has developed and investigated a spindle-through coolant supply method which can effectively supply an oil mist to the cutting area at the rate of 0.02-0.04 ml/min. The study was conducted both in drilling and end-milling using 27,000 ml/min as a benchmark for flood application. The result showed that the drilling with minimal cutting fluid application provided almost the same performance as conventional drilling with flood application but a considerable advantage was obtained in end milling.

In 2002, A. S. Vadarajan et al. introduced a new minimal cutting fluid application technique which mist is not generated. In this method small quantity of cutting fluid was applied in form of high velocity, narrow, pulsed jet. The amount of cutting fluid was only 2 ml/min as an injection pressure 20 MPa and pulsing rate of

600 pulse/min. An experiment was conducted in hard turning of hardened tool steel (AISI 4340). Results indicated that the overall performance during minimal cutting fluid application was superior to that during dry turning and conventional wet turning on the basis of cutting force, tool life, surface finish, cutting ratio, cutting temperature and tool-chip contact length. It should be noted that the research was done at moderate cutting speeds in turning where focusing a pulsed jet to the cutting zone poses no problem as the cutting tool is stationary. This process also can be done on high speed milling as proven by Thanongsak Thepsonthi in May 2005 with his paper “Investigation into minimal cutting fluid application in high speed milling of hardened steel using carbide mills”.

Table 2.1: The Analytical Review of MQL Method

No.	Research by	Method of Research	Type of Machining Process	Type of Workpeice	Type of Lubrication	Benchmark Flow Rate, Q (Flood Lubrication)	Face of Machining	Flow Rate, Q	Pressure, P	Analytical Review by Author
1	A. R. Machado and J. Wallbank, 1997	Flowing the lubrication with a fast air stream	Turning	Medium Carbon Steel (AISI 1040)	Water and Soluble Oil	5,200 ml/mim	Rake Face	3.3 - 5 ml/min	0.2 MPa	1. The result showed that surface finish, chip thickness and force variation were all affected beneficially compared to flood coolant. If looked to the benchmark of flood coolant at 5,200 ml/min flow rate, this method only use 1% of lubrication compare to benchmark.
2	Toshiaki Wakabayashi et al., 1998	Air containing uniform and extremely low concentration	Turning	Carbon Steel (S45C)	Neat Cutting Oil (non-soluble oil)	4,000 ml/min	Rake face and flank face	0.01 - 0.16 ml/min	0.6 MPa	1. The study was concluded that the result was almost equal to conventional method in terms of prevention of tool wear, improvement of surface finish and control of built-up edge. Benchmark comparison equal to 0.005% usage of lubrication
3	Tea Jo Ko et al., 1999	Oil mist application with Air-Cooling Using a Vortex Tube	Turning	Carbon Steel (1010)	Air with Neat Cutting Oil (non-soluble oil)	NA	Rake face and flank face	NA	NA	1. The system is similar to a conventional mist coolant system except that it uses cooled air. The cooled air with oil mist ejected at the tip of the cutting tool lowers the tool temperature, and reduced the wear of a TiN coated tool to give 30% of CBN tool life at the same cutting length. Figure 2.4 shows the schematic diagram of the air vortex tube.
4	M. Rahman et al., 2002	Superfine particle oil mist application	End Milling	Plastic mould steel (ASSAB 718HH)	Chilled Air	42,000 ml/min	Rake face and flank face	0.15 ml/min	0.52 MPa	1. Results indicated that mist application can be considered as an alternative to flood application at 42,000 ml/min owing to the drastic reduction (1/300,000 times) in lubricant consumption.
5	Durval U. Braga et at., 2002	Oil in flow of compressed air	Drilling	Aluminum-silicon alloys (SAE 323)	Soluble Oil	NA	Rake face and flank face	10ml/h	4.5 bars	1. The result showed that minimal cutting fluid application has the similar performance compared to flood application.
6	I. Aoyama, 2002	Spindle through coolant supply method	Drilling and End Milling	Carbon Steel	Soluble Oil	27,000 ml/min	Rake face and flank face	0.02 - 0.04 ml/min	NA	1. The result showed that the drilling with minimal cutting fluid application provided almost the same performance as conventional drilling with flood application but a
7	A. S. Vadarajan et al., 2002	Small quantity of cutting fluid was applied in pusle jet form	Turning	Hardened tool steel (AISI 4340)	Soluble Oil	NA	Rake face and flank face	2 ml/min at 600 pulse/min	20MPa	1. Results indicated that the overall performance during minimal cutting fluid application was superior to that during dry turning and conventional wet turning on the basis of cutting force, tool life, surface finish, cutting ratio, cutting temperature and tool-chip contact length. 2. It should be noted that the research was done at moderate cutting speeds in turning where focusing a pulsed jet to the cutting zone poses no problem as the cutting tool is stationary

2.5 Problem related to cutting fluids

Cutting fluids may contain other substances such as emulsifiers, stabilizers, corrosion inhibitors, biocides, fragrances, extreme pressure additives (EP additive), and contaminants. These complex mixtures are very useful but can cause a variety of health problems such as dermatitis, asthma, and hypersensitivity pneumonitis (HP).

Cutting fluid can form a mist of small droplets that are suspended in the air and can be inhaled and ingested. When these fluids form into a mist during the machining process, they can be very irritating to the eyes, nose, and throat. The larger droplets can pass into the nose and windpipe and can be swallowed. The smaller droplets can deposit into the lungs (Stephen L. Gauthier, 2003). This also includes not only oil mist, but also breathing in dust, fumes, and vapors from solvents and various gases.

During the machining process, a considerable amount of heat is generated at the cutting zone and may produce vapors resulting from the heating of the cutting fluids. The vapor then is produced as a result of boiling. Vapor generated then may condense to form mist.

The inhalation of cutting fluids mist, vapors, and smoke over a period of time may cause asthma or hypersensitivity pneumonitis. Exposure to mineral oil mists can cause eye, skin, and upper respiratory tract irritation as well as central nervous system effects in humans. In addition, certain mineral oils are carcinogenic in humans. Exposure to mineral oil mists can result in localized irritation of the mucous membranes, and if exposures are excessive, headaches, dizziness, and drowsiness may result. Many studies confirm that poorly refined mineral oil can induce skin and scrotal cancers after prolonged, repeated, and heavy direct contact with the skin (Stephen L. Gauthier, 2003). In addition, repeated dermal exposures may result in dermatitis. Aspiration of mineral oil mists into the lungs can result in blue coloration of the skin, rapid heartbeat, fever, and chemical pneumonia possibly followed by a secondary infection. Ingestion will cause a burning sensation in the mouth, throat, and stomach followed by vomiting, diarrhea, and belching.

There are some regulations applied in order to protect worker from danger of cutting fluid mist. For example; in 1999 the Occupational Safety and Health Administration (OSHA) Metalworking Fluids Standards Advisory Committee also

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